Nuclear Reactions
with respect to other changes

Energy drives all reactions, physical, chemical, biological, and nuclear.

Physical reactions change states of material among solids, liquids, gases, solutions. Molecules of substances remain the same.

Chemical reactions change the molecules of substances, but identities of elements remain the same.

Biological reactions are combinations of chemical and physical reactions.

Nuclear reactions change the atomic nuclei and thus the identities of nuclides. They are accomplished by bombardment using subatomic particles or photons.

Nuclear Reactions

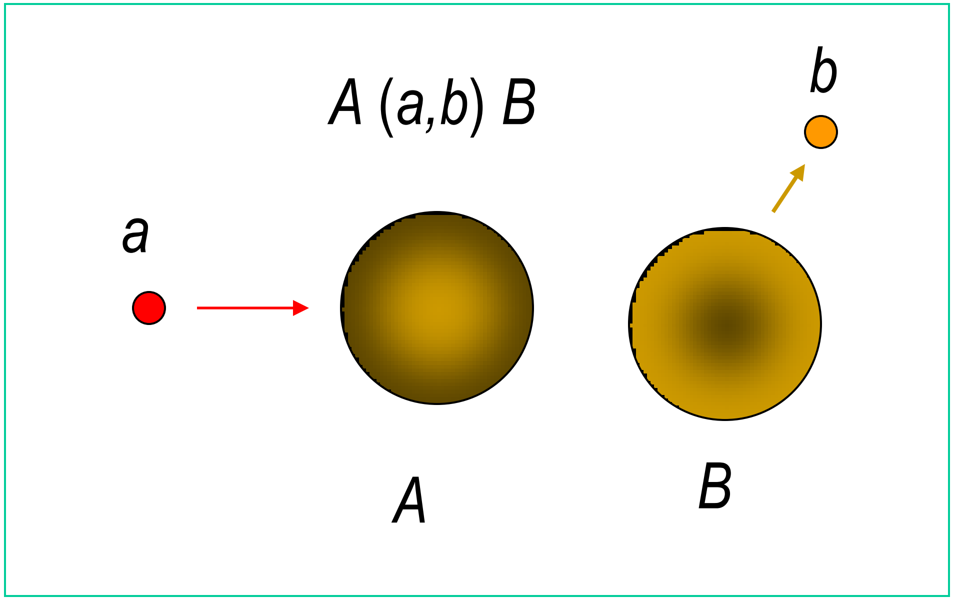
changing the hearts of atoms

Nuclear reactions, usually induced by subatomic particles *a*, change the energy states or number of nucleons of nuclides.

After bombarded by *a*, the nuclide *A* emits a subatomic particle *b*, and changes into *B*.

$$a + A \rightarrow B + b$$

or written as *A* (*a*,*b*) *B*



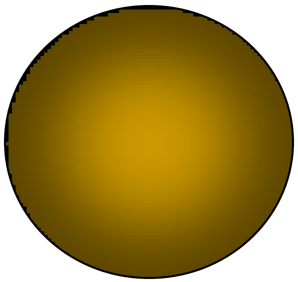
Describe nuclear reactions

Subatomic Particles for and from Nuclear Reactions

Subatomic particles used to bombard or emitted in nuclear reactions:

γ	photons
β	electrons
p or ^{1}H	protons
n	neutrons
d or ^{2}D	deuterons
t or ^{3}T	tritons
α or ^{4}He	alpha particles
^{n}E	atomic nuclei

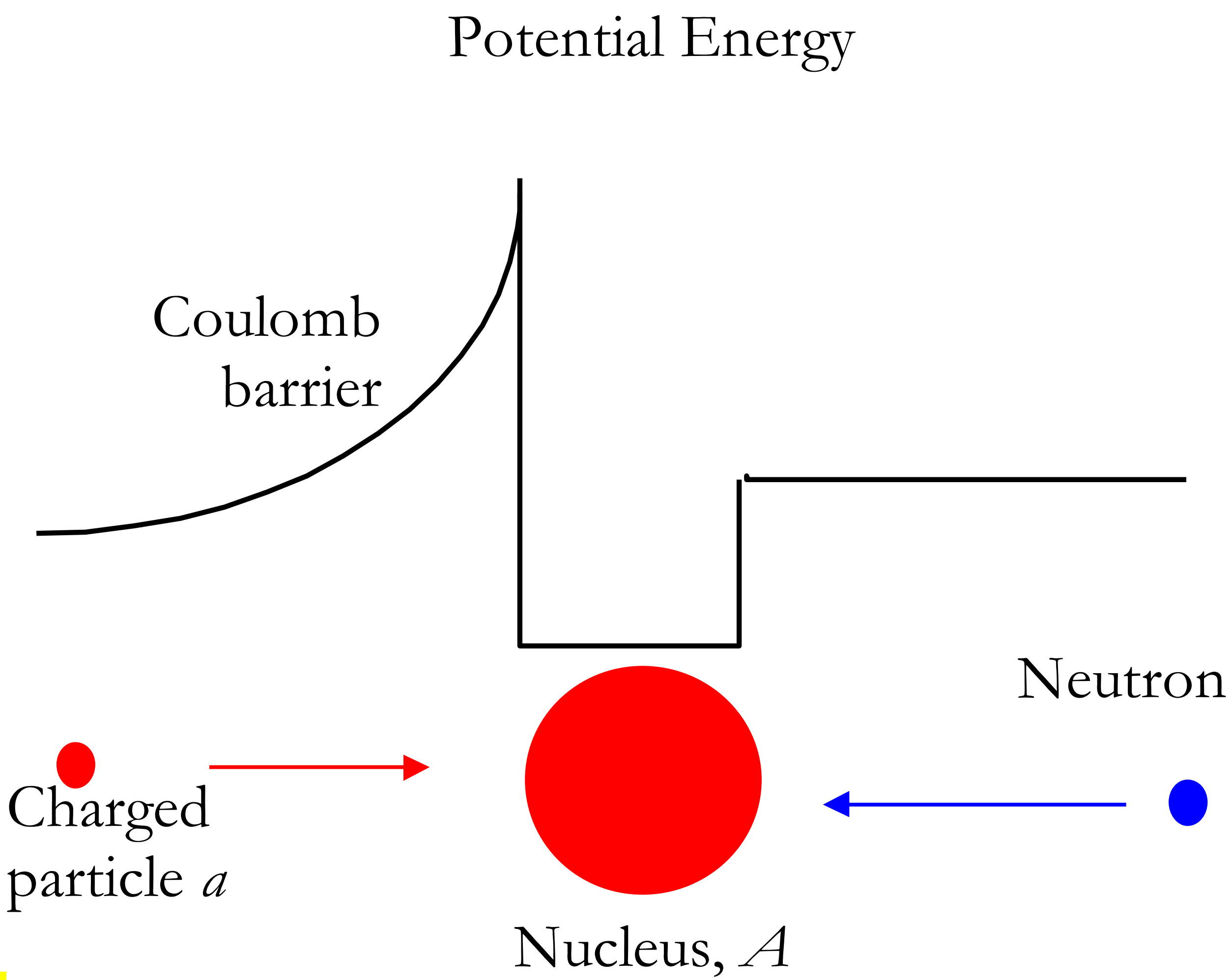
Endothermic reactions require energy.



exothermic reactions release energy.

The Potential Energy of a Positively Charged Particle as it Approaches a Nucleus.

Potential Energy of Nuclear Reactions



Explain interaction of particle with nuclei

Estimate Energy in Nuclear Reactions

The energy Q in a reaction A (a, b) B is evaluated according to

$$m_a + m_A = m_b + m_B + Q, \qquad \text{(Q differs from enthalpy)}$$

where m_i means mass of i etc

$$Q = m_a + m_A - (m_b + m_B) \qquad \text{(difference in mass before and after the reaction)}$$

The Q is positive for exothermic (energy releasing at the expense of mass) or negative for endothermic (requiring energy) reactions.

For endothermic reactions, the energy can be supplied in the form of kinetic energy of the incident particle. Energy appear as kinetic energy of the products in exothermic reactions.

Endothermic and Exothermic Reactions

These two examples illustrate endothermic and exothermic reactions.

Example: Energy for the reaction

$$^{14}N \quad + \quad ^{4}He \quad \rightarrow \quad ^{17}O \quad + \quad ^{1}H \quad + \quad Q$$

$$14.00307 + 4.00260 = 16.99914 + 1.007825 + Q$$

$$Q = 14.00307 + 4.00260 - (16.99914 + 1.007825) = -0.001295 \text{ amu}$$

$$= -1.21 \text{ MeV}$$

endothermic, kinetic energy of α must be greater than 1.21 MeV

Example: The energy Q for the reaction $^{11}B(\alpha, n)\ ^{14}N$, given masses: ^{11}B, 11.00931; n, 1.0086649.

$$Q = 11.00931 + 4.00260 - (1.0086649 + 14.00307) = 0.000175 \text{ amu}$$

$$= 0.163 \text{ MeV}$$

exothermic reaction

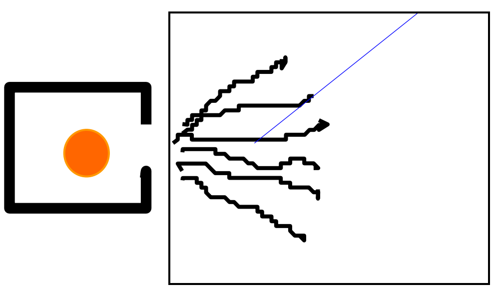
Discoveries of Nuclear Reactions

In 1914, Marsden and Rutehrford saw some thin tracks and spots among those due to α particles. They attributed them to protons and suggested the nuclear reaction:

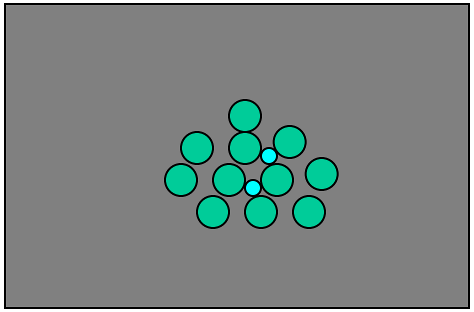
$$^{14}N + {}^{4}He \rightarrow \; {}^{17}O + {}^{1}H \quad \text{or} \quad {}^{14}N\,(\alpha, p)\,{}^{17}O$$

F. Joliot and I. Curie discovered the reaction

$$^{27}Al\,(\alpha, n)\,{}^{30}P\,(\;,\,\beta^{+}\text{ or EC})\,{}^{30}Si, \quad \text{half life of } {}^{30}P \text{ is 2.5 min}$$



α source & tracks with thin proton track



α and thin proton spots on fluorescence screen

Smashing the Atoms

In 1929, John Cockroft and Ernest Walton used 700,000 voltage to accelerate protons and bombarded lithium to induce the reaction,

$$^{7}Li + p \rightarrow 2\,\alpha$$

They called it smashing the atoms, a mile stone in the discovery of nuclear reaction. This reaction is also a proton induced fission, and illustrates the stability of the helium nuclide.

They received the Nobel prize for physics in 1951.

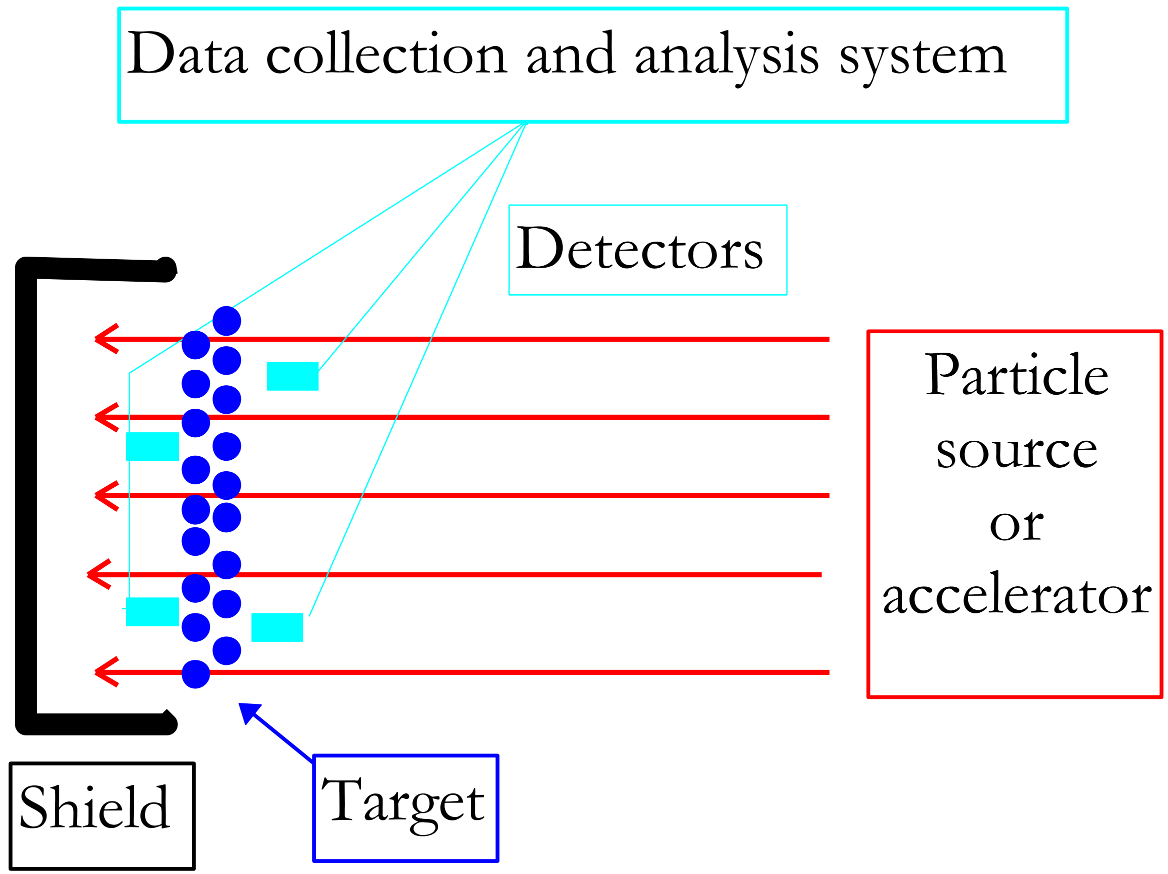
Use the discover of n.r. to explain n.r.

Nuclear Reaction Experiments

Basic Components

particle source
target
shield
detectors
data collection
data analysis system

A Setup for Nuclear Reactions



Neutron Sources for Nuclear Reactions

Neutrons are the most important subatomic particles for inducing nuclear reactions. These sources are:

- Neutrons from α induced nuclear reactions
- Neutrons from γ-photon excitations
- Neutrons from nuclear reactions induced by accelerated particles
- Neutrons from spontaneous and n-induced fission reactions (nuclear reactors)

Know how to get neutrons

Neutrons from α Induced Reactions

The discovery of neutron by James Chadwick in 1932 by reaction

$^{9}Be\ (\alpha, n)\ ^{12}C$,

was applied to supply neutrons for nuclear reactions by mixing α-emitting nuclides with Be and other light nuclides.

Mixtures used as neutron sources

Source	Reaction	n energy / MeV
Ra & Be	$^{9}Be(\alpha, n)^{12}C$	up to 13
Po & Be	$^{9}Be(\alpha, n)^{12}C$	up to 11
Pu & B	$^{11}B(\alpha, n)^{14}N$	up to 6
Ra & Al	$^{27}Al\ (\alpha, n)^{31}P$	

Neutrons by γ Excitation

High-energy photons excites light nuclides to release neutrons. To avoid α- and β-ray excitation, radioactive materials are separated from these light nuclides in these two-component neutron sources to supply low energy neutrons for nuclear reactions.

Two-component neutron sources

Source	Reaction	n energy / MeV
^{226}Ra, Be	^{9}Be(γ, n)^{12}C	0.6
^{226}Ra, D_2O	^{2}D(γ, n)^{1}H	0.1
^{24}Na, Be	^{9}Be(γ, n)^{8}Be	0.8
^{24}Na, H	^{2}D(γ, n)^{1}H	0.2

Neutrons from Accelerators and Reactors

Neutrons are produced from nuclear reaction using energetic particles from accelerators.

^{2}D (d, n) ^{3}He

^{3}T (d, n) ^{4}He

Neutrons from nuclear fission reactions

^{252}Cf spontaneous fission to yield 3 or more neutrons

^{235}U and ^{239} Pu induced fission reactions release 2 to 3 neutrons in each fission

Neutron Induced Radioactivity

Using neutrons from the reaction, $^{27}Al\ (\alpha, n)^{31}P$, Fermi's group in Italy soon discovered these reactions:

$^{19}F\ (n, \alpha)\ ^{16}N$

$^{27}Al\ (n, \alpha)\ ^{24}Na\ (, \beta)\ ^{24}Mg$.

They soon learned that almost all elements became radioactive after the irradiation by neutrons, in particular

$^{10}B\ (n, \alpha)\ ^{7}Li$ releasing 2.3-2.8 MeV energy

is used in classical neutron detectors. Now, detectors use,

$^{3}He\ (n, p)\ ^{3}H$

Application of neutrons

Nuclear Reactions Induced by Cosmic Rays

Cosmic rays consist of mainly high energy protons, and they interact with atmospheres to produce neutrons, protons, alpha particles and other subatomic particles.

One particular reaction is the production of ^{14}C,

$^{14}N(n, p)^{14}C$ - β emitting, half-life 5730 y

Ordinary carbon active in exchange with CO_2 are radioactive with 15 disintegration per minute per gram of C.

Applying decay kinetics led to the ^{14}C-dating method.

Light-Nuclide Nuclear Reactions

Reaction	Measured Q (MeV)	Reaction	Measured Q (MeV)
$^{2}H(n,\gamma)^{3}H$	6.257 +/- 0.004	$^{9}Be(p,\alpha)^{6}Li$	2.132 +/- 0.006
$^{2}H(d,p)^{3}H$	4.032 +/- 0.004	$^{10}B(n,\alpha)^{7}Li$	2.793 +/- 0.003
$^{6}Li(p,\alpha)^{3}H$	4.016 +/- 0.005	$^{10}B(p,\alpha)^{7}Be$	1.148 +/- 0.003
$^{6}Li(d,p)^{7}Li$	5.020 +/- 0.006	$^{12}C(n,\gamma)^{13}C$	4.948 +/- 0.004
$^{7}Li(p,n)^{7}Be$	-1.645 +/- 0.001	$^{13}C(p,n)^{13}N$	-3.003 +/- 0.002
$^{7}Li(p,\alpha)^{4}He$	17.337 +/- 0.007	$*^{14}N(p,n)^{14}C$	-0.627 +/- 0.001
$^{9}Be(n,\gamma)^{10}Be$	6.810 +/- 0.006	$^{14}N(n,\gamma)^{15}N$	10.833 +/- 0.007
$^{9}Be(\gamma,n)^{8}Be$	-1.666 +/- 0.002	$^{18}O(p,n)^{18}F$	-2.453 +/- 0.002
$^{9}Be(d,p)^{10}Be$	4.585 +/- 0.005	$^{19}F(p,\alpha)^{16}O$	8.124 +/- 0.007

Particle Accelerators

A DEVICE that provides forces on charged particles by some combination of electric and magnetic fields and brings the ions to high speed and kinetic energy is called an accelerator.

The accelerators used for nuclear structure studies may be classified into those that develop a steady accelerating field (DC machines) and those in which radio frequency electric fields are used (AC machines). All accelerators for particle physics are of the latter type. We will start later on with a brief description of DC machines.

The sources-accelerators that can be used to obtain energetic charged particles, and secondarily neutrons and photons, that can induce nuclear reactions or chemical changes.

Charged Particle Accelerators

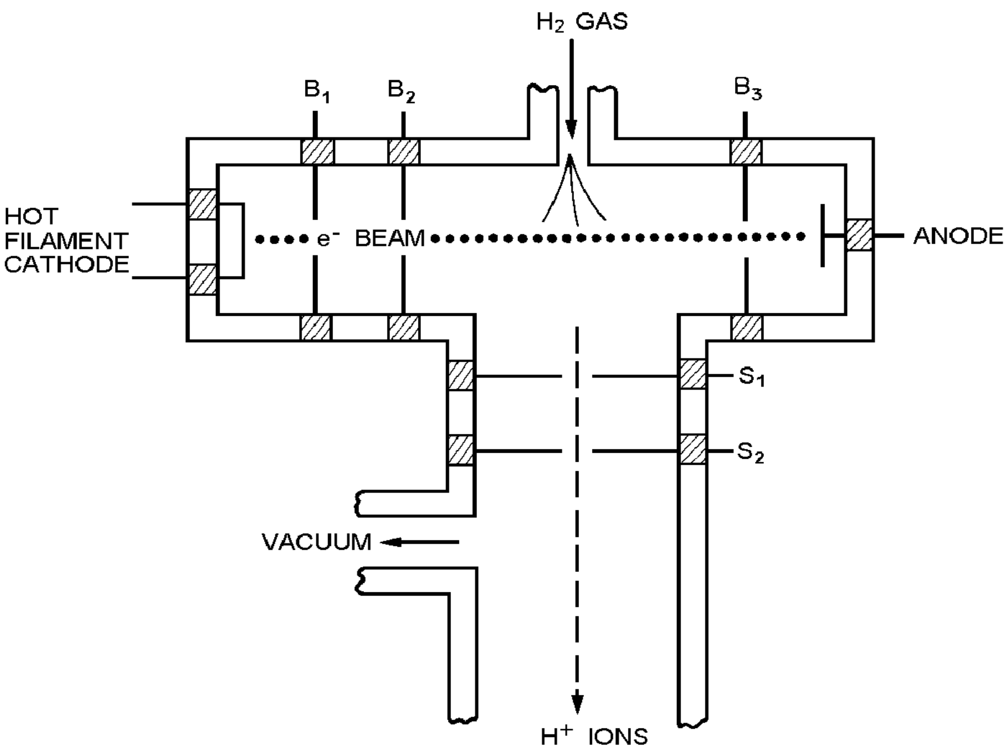
The principle to be used to achieve the higher kinetic energies was obvious. The projectile particles would have to be ionized to obtain positively charged ions. If these ions could be accelerated through a potential difference of 1000 V, they would acquire 1000 eV additional kinetic energy, per unit of charge. If an α-particle of a +2 charge was to be accelerated through a potential difference of 10^6 V, it would acquire an additional kinetic energy or 2 MeV.

The problem of obtaining the desired kinetic energy involved two aspects: first, the production of the charged particles: second, the acceleration through the necessary potential difference, where both nuclear and particle physics experiments are typically performed at accelerators, where particles are accelerated to extremely high energies, in most cases relativistic (i.e., $v \approx c$).

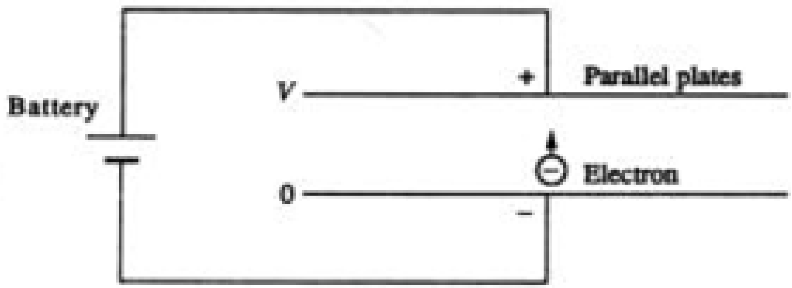
Target

There are two ways to make the necessary collisions with the accelerated beam: Fixed target and colliding beams. In fixed target mode the accelerated beam hits a target which is fixed in the laboratory. In the case of colliding beams we use the fact that we have (say) an electron beam moving one way, and a positron beam going in the opposite direction.

Ion Source

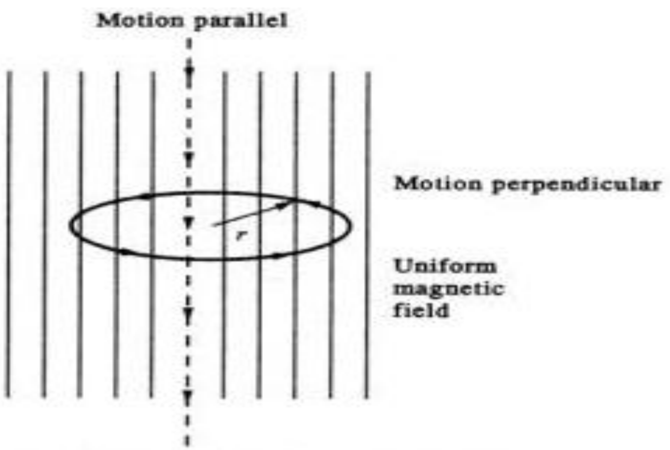


Electric and Magnetic Forces



Capacitor as accelerator.

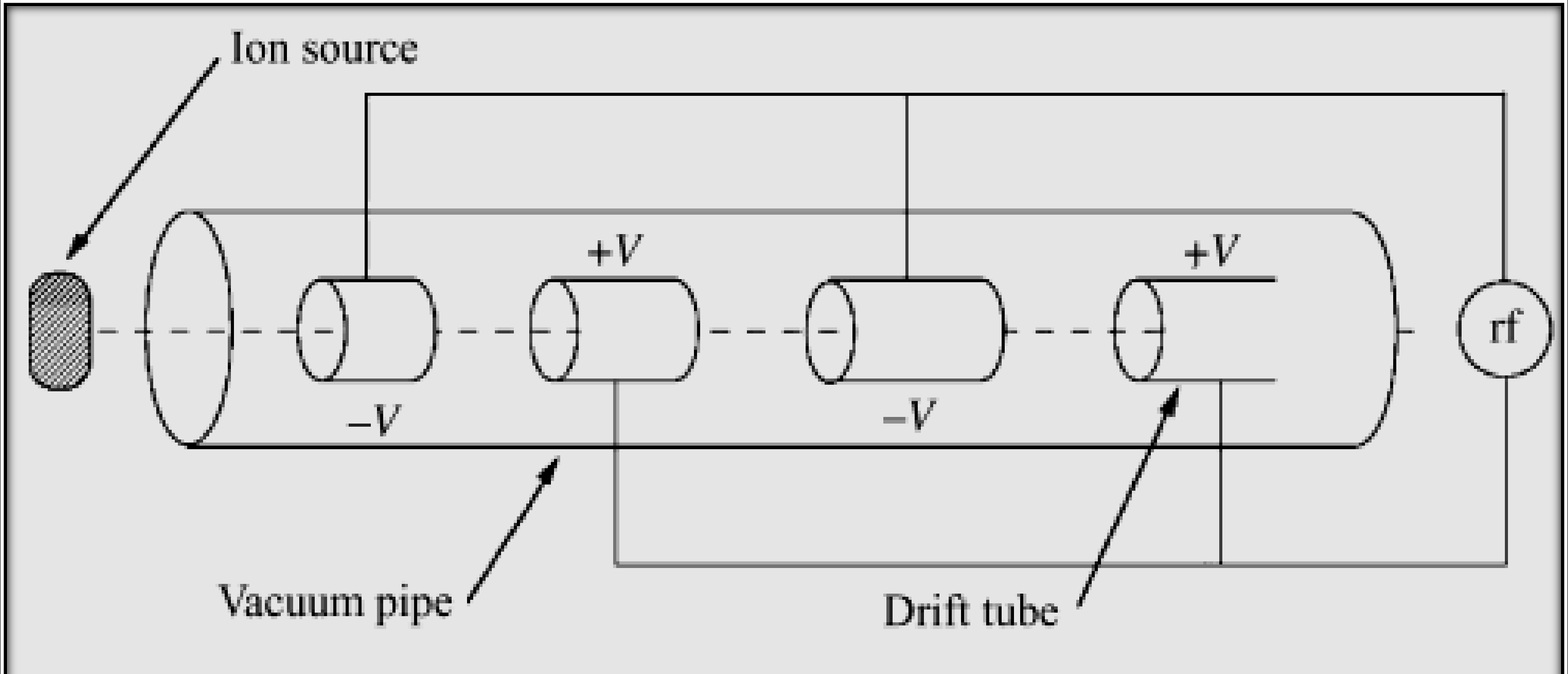
$$v = \sqrt{2Ve / m}$$



Electric charge motion in uniform magnetic field.

$$\omega = eB/m$$

Resonance Accelerators
Multiple-stage linear accelerator
(Linac or Linear Accelerator)



Acceleration in a linear ion accelerator